

# 1. INTRODUCTION

The  ${}^4\text{He}(p,d){}^3\text{He}$  reaction possesses some appealing theoretical features. The nuclear structure involved is relatively simple since essentially only 1S orbitals can participate. Furthermore, the wavefunctions can be constrained by the wealth of experimental information on  ${}^3\text{He}$  and  ${}^4\text{He}$ . This permits investigation of the reaction mechanism with a minimum of additional theoretical uncertainties. In particular, one may be able to learn about the role of pion emission and absorption processes as well as intermediate  $\Delta$  formation in the  $(p,d)$  process. For such light systems exchange processes, in this case the two nucleon pick-up process  ${}^4\text{He}(p, {}^3\text{He}){}^2\text{H}$ , may also be important. In addition, knowledge of the cross sections over a wide energy range is useful in astrophysical calculations of the production of  ${}^3\text{He}$ . While there have been several studies at proton energies less than 100 MeV, there are very few published data at higher energies where there is a large momentum transfer. In addition, analyzing power measurements, which are most important in trying to assess the validity of the reaction mechanism being used, have only been taken at 32 and 50 MeV, although some unpublished data exist at 650 and 800 MeV.<sup>1</sup> In order to provide additional intermediate energy data on this reaction, the present measurements have been made at TBMF using the 1.4 GeV/c spectrometer and beams of polarized protons of 200 and 400 MeV.

Although the details of the reaction mechanism appropriate for the  $(p,d)$  reaction on a very light target at an energy of several hundred MeV are not entirely clear, the data to be presented will be compared to exact-finite-range distorted wave calculations using the adiabatic approximation for the deuteron potential. These calculations will at least serve as a reference frame for discussing additional aspects of the

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${}^4\text{He}(p,d){}^3\text{He}$  Reaction at 200 and 400 MeV

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reaction mechanism that should be included in the calculations. In order to provide a consistent set of energy dependent optical potential parameters for the proton channel, proton -  ${}^4\text{He}$  elastic scattering data from 85 to 800 MeV were fitted using a search procedure. Distorted-wave calculations were carried out and comparisons were made with existing data at 156 MeV<sup>2</sup> and 770 MeV<sup>3</sup> as well as with the data presented in this paper.

## II EXPERIMENTAL PROCEDURES

A polarized proton beam from the TRIUMF cyclotron was used in conjunction with the 1.4 GeV/c magnet spectrometer (MRS) and a liquid  ${}^4\text{He}$  target to carry out the measurements. Details of the apparatus and the method used in determining the polarization of the beam<sup>4-6</sup> and the construction of the liquid  ${}^4\text{He}$  target<sup>7,8</sup> have been published previously. The polarization of the beam was typically 80 to 70% and was monitored continuously during a run by a polarimeter and a thin  $\text{CH}_2$  foil that was inserted in the beam. The beam polarization was known to  $\pm 0.03$ . The liquid  ${}^4\text{He}$  was about 33 mg/cm<sup>2</sup> thick and was contained in a cell that had separate Kapton and nickel windows that were 0.15 mg/cm<sup>2</sup> thick.

The essential features of the magnetic spectrometer that are relevant to the present experiment have also been described previously.<sup>9</sup> The momentum acceptance of the spectrometer was set at about  $\pm 7\%$ . Deuteron spectra at 200 and 400 MeV taken during the measurements have been published<sup>10</sup> and the deuteron group to the ground state of  ${}^3\text{He}$  is well resolved from the continuum with little background contribution.

Normalization of the cross sections was based on elastic  ${}^4\text{He}(p,p)$  data, which were taken at 200 MeV at scattering angles of 16, 30 and 45° and compared to the published cross sections of Moss et al.<sup>11</sup> It is estimated that the uncertainty in the absolute values of the cross sections

is no larger than 20%.

The cross sections at 200 and 400 MeV are displayed in Fig. 1 and the analyzing power data in Fig. 2; the numerical values are shown in Table I. The error bars shown on these data are based on statistics only. Also shown in Fig. 1 as the open circles are the back angle cross section measurements of Cameron et al.<sup>12</sup> at 400 MeV.

## III DISTORTED WAVE CALCULATIONS

In order to provide optical model parameters for the incident protons in the DWBA calculations, a series of parameter searches were carried out with proton elastic scattering data on  ${}^4\text{He}$  that ranged in energy from 85 to 800 MeV. Explicitly elastic cross section and analyzing power data at 85 MeV,<sup>13</sup> 200, 350 and 500 MeV,<sup>11</sup> and 800 MeV<sup>14</sup> were used with the search program MAGALI,<sup>15</sup> which was extended to include relativistic kinematics.

In the search procedure the values of  $r_0$  and  $a_0$ , the radius and diffuseness parameter of the real potential, were fixed at 1.244 and 0.206 fm, and  $a_1$ , the diffuseness parameter for the imaginary volume potential, was fixed at 0.336 fm. With these restraints optimum values for  $V_R$ ,  $W_I$ ,  $W_1$ ,  $V_{d0}$ ,  $r_{d0}$ , and  $a_{d0}$  were obtained for the elastic data at the five energies. In this way curves could be constructed for these parameters that varied smoothly in energy. The proton parameters at the four energies of interest for the (p,d) reaction were then taken from these plots and their values are shown in Table II.

The deuteron optical potentials used were based on the adiabatic deuteron approximation of Johnson and Soper.<sup>16</sup> This was done in part because very few deuteron -  ${}^3\text{He}$  elastic scattering data are available in the energy range of interest but mainly because the adiabatic model compensates for the deuteron break-up effects. The actual deuteron

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parameters that were used are shown in Table II and were constructed from the  $p^4\text{He}$  potential parameters at one half the corresponding deuteron laboratory energy generally following the prescription of Harvey and Johnson,<sup>17</sup> while taking into account that the deuteron scatter from  $^3\text{He}$  rather than  $^4\text{He}$ .

For the bound state of the transferred nucleon two form factors were used. The first form factor was a simple Gaussian 15 wave function from a harmonic oscillator well with a harmonic oscillator parameter,  $b=1.42$  fm.<sup>18</sup> This oscillator parameter was obtained by fitting the momentum distribution of protons measured in the  $^4\text{He}(e,e'p)$  reaction<sup>19</sup> with a Gaussian function.

The second form factor was derived using a procedure derived by Shepard et al.<sup>20</sup> Here the charge form factor obtained from electron- $^4\text{He}$  elastic scattering data was modified by subtracting pion exchange current contributions to give a true nucleon density. A Fourier transform was then taken of the modified charge density to yield a form factor whose numerical values were directly used in DWUCKS.<sup>21</sup> This exact-finite-range program allows for the inclusion of non-local effects by the introduction of a non-locality parameter,  $\beta$ . The values that were used at all energies were 0.85 for the incoming proton and 0.54 for the outgoing deuteron.

Calculations were also carried out for both form factors with the non-local parameter set equal to zero. In the calculations shown a spectroscopic factor of 2 has been assumed and is included in the calculations.

#### IV Conclusions

The comparison of the distorted wave calculations with the  $^4\text{He}(p,d)$  cross section data is shown in Figs. 1, 3, and 4. At all four energies the theoretical description of the data is relatively poor. While the general

magnitude of the cross sections is not in bad agreement, the detailed slopes of the theoretical angular distributions miss the shapes of the experimental data in a rather fundamental way. The differences between the calculations carried out with the two different form factors for the bound state calculation are relatively minor except at 770 MeV, where the Gaussian form factor provides far less structure than does the one based on the charge density distribution of  $^4\text{He}$ .

As shown in Fig. 2, the calculations provide a reasonable description of the analyzing power data. At 400 MeV the description is most encouraging. The results of the calculations with the non-local parameter,  $\beta$ , set equal to zero are not shown in the figures. The effect on the cross sections of having  $\beta=0$  was negligible. The effect on the analyzing power prediction at 156 and 200 MeV was to reduce rather drastically the magnitudes of  $A_y$ . At 400 and 770 MeV the effect was to change completely the angular dependence such as to destroy any agreement with the 400 MeV data.

It is clear that the pickup reaction mechanism that has been assumed is in general not accounting for the data in an adequate fashion. Apart from the direct one nucleon transfer process there are additional processes that may contribute to the  $^4\text{He}(p,d)$  cross sections. Some of these are presented by the diagrams in Fig. 5. Figure 5a pictures the direct one nucleon transfer assumed in the DWBA calculations presented. Figure 5b represents the "heavy particle stripping" contributions, which involve here a direct two nucleon transfer. This coherent contribution is certainly expected to be more important here than for the case of a  $(p,d)$  reaction on heavier nuclei, where the heavy particle stripping involves the transfer of a (much) larger nuclear cluster. Calculations that include this exchange

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contribution are being pursued. The rise in the cross sections at scattering angles greater than about  $100^\circ$  is clearly seen in the 156 MeV data and in the 400 MeV data between  $160^\circ$  and  $180^\circ$ . This is no doubt mainly due to the two nucleon transfer. In fact plane wave calculations carried out by Bernas et al.<sup>2</sup> account for this general back angle rise in the cross sections in terms of this process. In a similar fashion, two-nucleon transfer calculations were carried out to account for the large angle (p,d) data taken at a proton energy of 85 MeV. It will be important to see the results for even the forward angle region when the one and two nucleon transfer contributions are added coherently.

Figures 5c and 5d represent processes in which the momentum transfer is shared between two nucleons, one nucleon becoming a delta. These processes may be expected to give substantial contributions at higher energies, because of the momentum mismatch which is especially important for  $l=0$  transitions. Calculations of the general type indicated in diagram 5(c) were carried out by A. Boudard et al.<sup>22</sup> for the  $^{16}\text{O}(d,p)^{17}\text{O}$  reaction at  $E_d=698$  MeV. Here the one-nucleon stripping cross sections alone overpredicted the measured cross sections by a factor of about 7. Inclusion of double pion rescattering with intermediate  $\Delta$  excitation had the general effect of reducing the predicted cross sections to achieve reasonable agreement with the data but the shape was poorly reproduced. In a subsequent publication, however, Shepard and Rost<sup>23</sup> were able to account reasonably well for these same data with an exact-finite-range single neutron transfer distorted wave calculation.

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Table I  
Cross sections and analyzing power data for the  ${}^4\text{He}(\vec{p}, d){}^3\text{He}$  reaction at 200 and 400 MeV

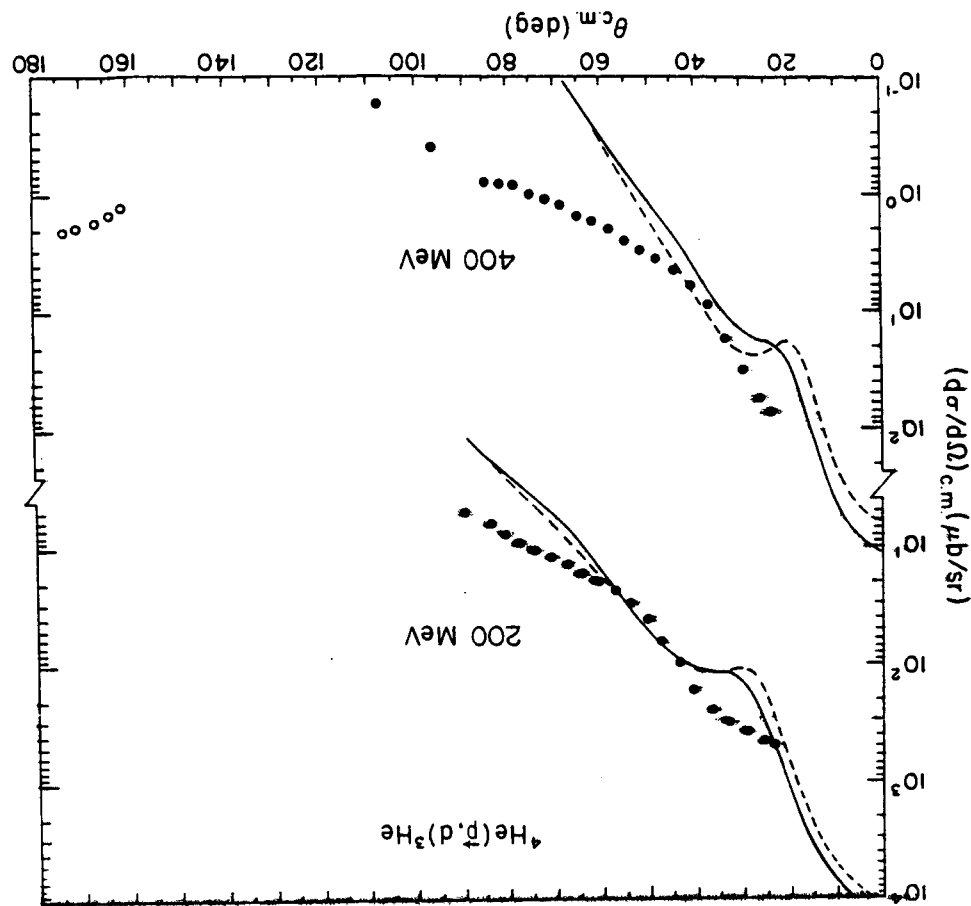
$E_p=200$ MeV	$\theta_{cm}$ (deg)	$d\sigma/d\Omega(\mu b/st)$	$c.m.$	$A_y$
	23.4	495±6		-0.41±0.02
	25.6	462±6		-0.25±0.02
	29.3	389±5		-0.01±0.02
	32.9	312±3		0.08±0.02
	36.5	246±3		0.15±0.02
	40.1	167±3		0.16±0.03
	43.6	97.7±0.8		0.25±0.01
	47.1	64.7±0.7		0.17±0.01
	50.6	42.3±0.4		0.16±0.01
	54.1	30.9±0.3		0.11±0.02
	57.6	23.9±0.2		0.15±0.01
	61.0	20.4±0.2		0.22±0.02
	64.3	17.4±0.2		0.29±0.02
	67.7	14.4±0.2		0.40±0.02
	71.0	12.5±0.2		0.44±0.02
	74.2	11.0±0.2		0.48±0.03
	77.5	9.4±0.2		0.51±0.03
	80.6	7.9±0.2		0.56±0.04
	83.8	6.4±0.3		0.59±0.05
	89.9	5.1±0.2		0.61±0.07
$E_p=400$ MeV				
	23.7	72±1		-0.32±0.02
	26.0	56.3±0.9		-0.31±0.02
	29.7	31.5±0.8		-0.34±0.02
	33.4	17.2±0.3		-0.29±0.02
	37.0	8.7±0.3		-0.03±0.03
	40.6	6.1±0.1		0.25±0.03
	44.2	4.5±0.1		0.44±0.04
	47.8	3.59±0.07		0.51±0.03
	51.3	3.05±0.08		0.39±0.04
	54.8	2.47±0.07		0.29±0.04
	58.2	2.04±0.07		0.35±0.05
	61.7	1.67±0.06		0.33±0.05
	65.1	1.55±0.04		0.25±0.03
	68.4	1.26±0.06		0.28±0.07
	71.7	1.11±0.06		0.35±0.08
	75.0	0.99±0.03		0.47±0.05
	78.2	0.85±0.04		0.52±0.06
	81.4	0.82±0.03		0.57±0.06
	84.5	0.78±0.05		0.66±0.09
	96.6	0.42±0.04		0.62±0.14
	107.7	0.17±0.03		0.51±0.30

Table II  
Optical Model Parameters[illegible]

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Figure Captions

- Figure 1 Angular distributions for the  ${}^4\text{He}(p,d){}^3\text{He}$  reaction taken with proton energies of 200 and 400 MeV. The solid lines are the results of exact-finite-range distorted wave calculations using a Gaussian shaped form factor for the bound state calculations and for the dashed line a form factor derived from electron scattering on  ${}^4\text{He}$  was used. The open circles at 400 MeV are from Ref. 12.
- Figure 2 Analyzing power data for the  ${}^4\text{He}(p,d){}^3\text{He}$  reaction at 200 and 400 MeV. The solid and dashed lines are the results of calculations described in Figure 1.
- Figure 3 Angular distribution for the  ${}^4\text{He}(p,d){}^3\text{He}$  reaction at 156 MeV (Ref. 2). The solid and dashed lines are the results of calculations as described in Figure 1.
- Figure 4 Angular distribution for the  ${}^4\text{He}(p,d){}^3\text{He}$  reaction at 770 MeV (Ref. 3). The solid and dashed lines are the results of calculations as described in Figure 1.
- Figure 5 Diagrams illustrating various possible contributions to the  ${}^4\text{He}(p,d){}^3\text{He}$  cross section. The one and two nucleon transfer are shown in (a) and (b) respectively. The process of interaction through a delta is shown in (c) and (d) either directly with the transferred neutron or with a spectator.



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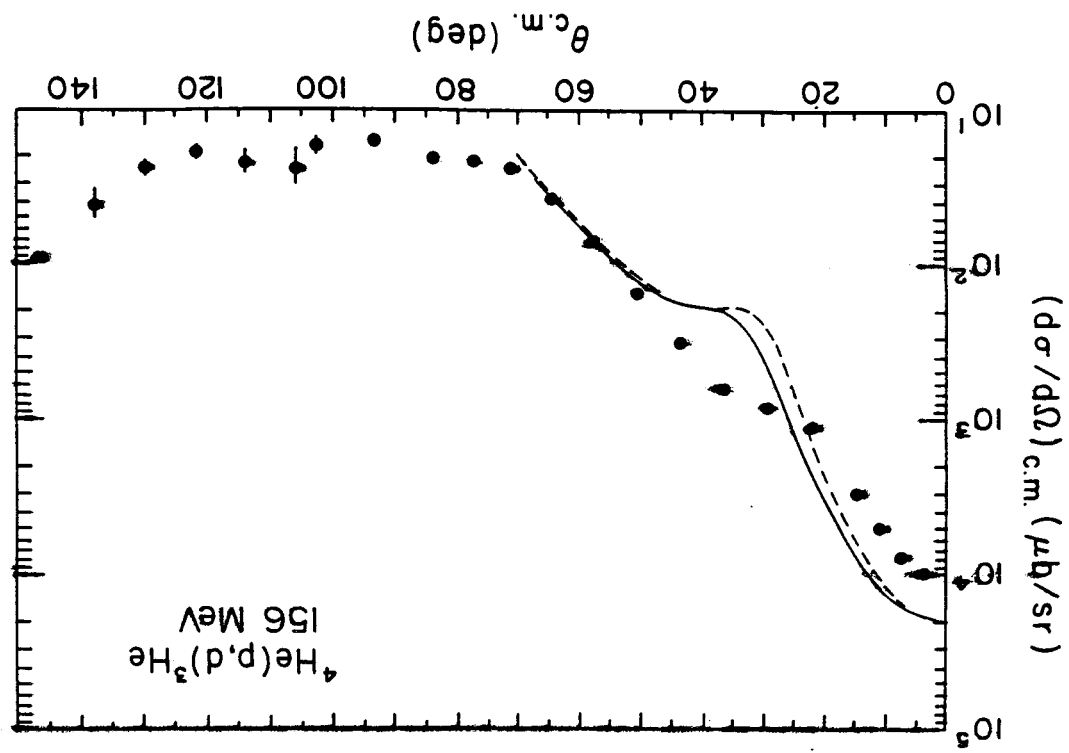
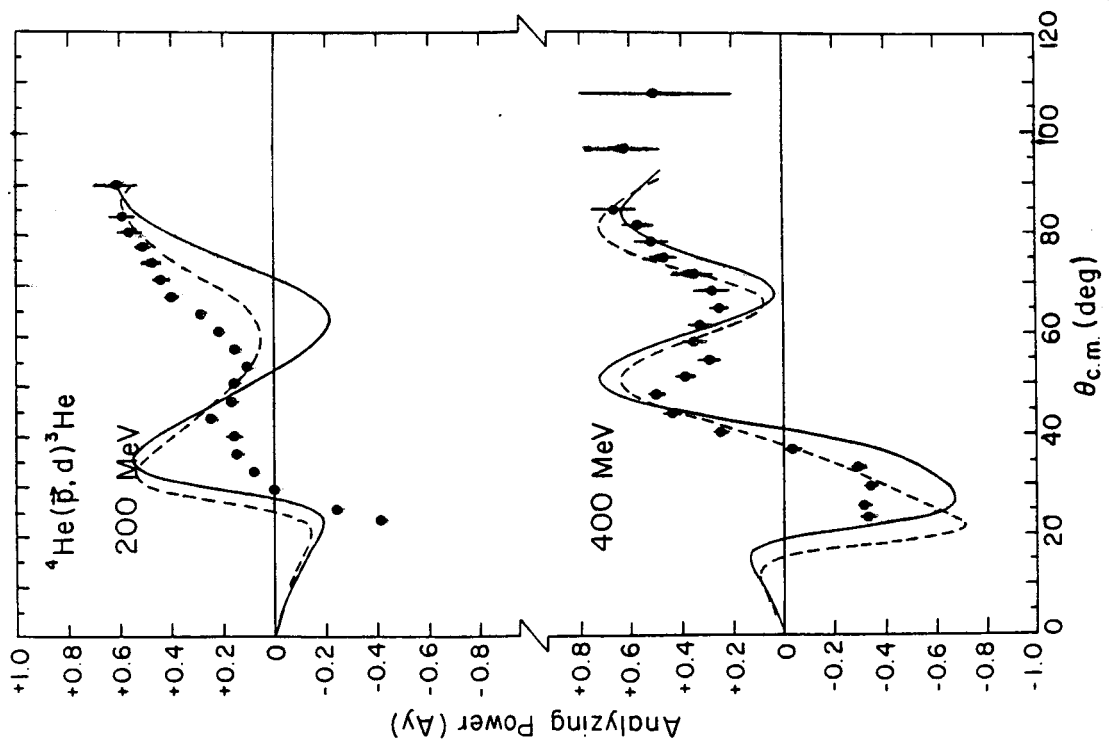




Fig 4

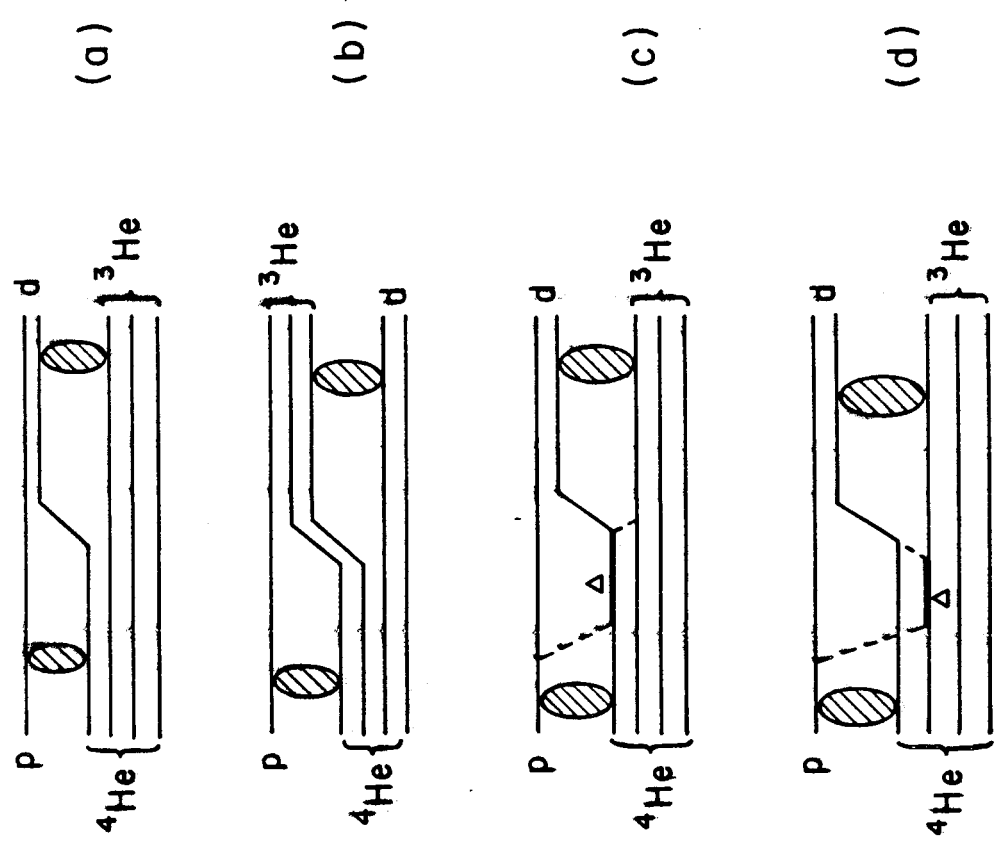
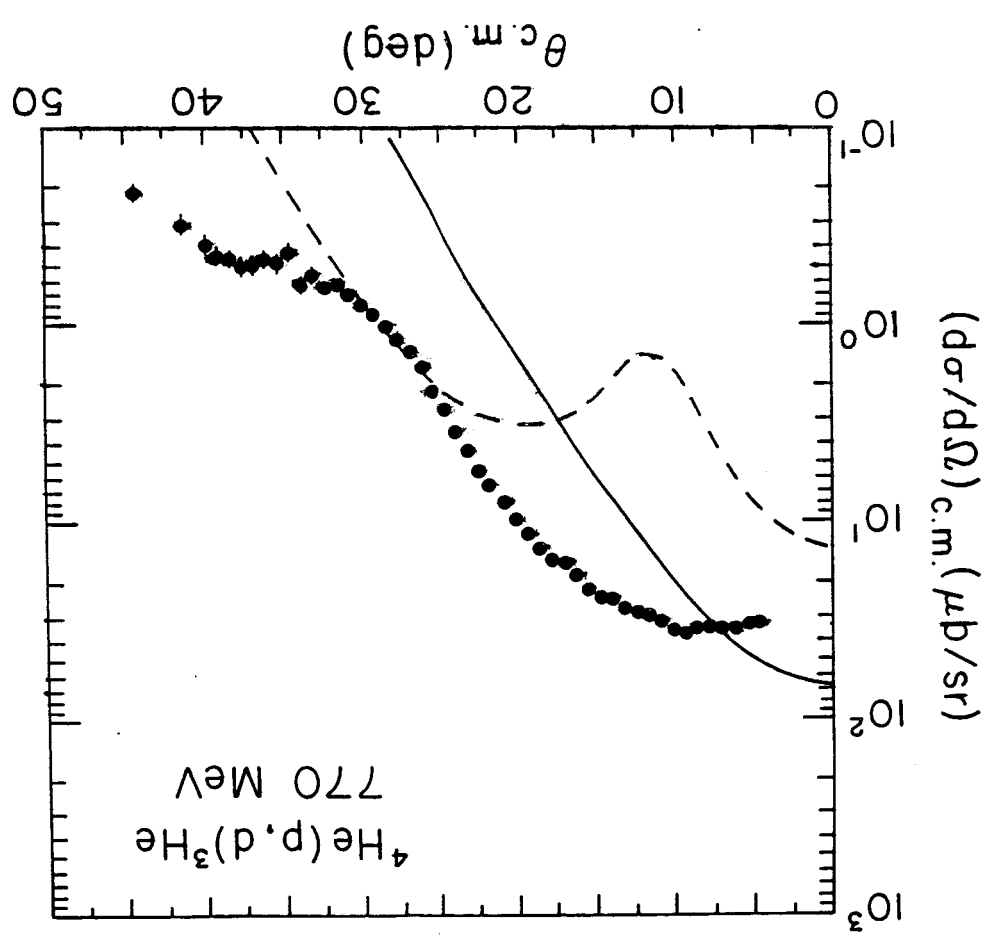


Fig 5